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Response Surface Methodology for Modelling Tribological Behaviour of Maraging Steel 300 Parts Manufactured by Laser Powder Bed Fusion

D. K. Maodzeka[1, a*)]; M. Mosalagae[1, b)]; D. Hagedorn-Hansen[2, c)]; S. L. Pityana[3, d)]; E. O. Olakanmi[1, e)]

[1] *Department of Mechanical, Energy & Industrial Engineering, Botswana International University of Science & Technology (BIUST), Palapye, Botswana.*
[2] *Department of Industrial Engineering, Stellenbosch University, Stellenbosch, South Africa.*
[3] *Laser Enabled Manufacturing (LEM) Research Group, National Laser Centre, Council for Scientific & Industrial Research (CSIR), Pretoria, South Africa.*

[a] *Corresponding author: md19100070@studentmail.biust.ac.bw*
[b] *mosalagaem@biust.ac.bw*
[c] *devonh@sun.ac.za*
[d] *SPityana@csir.co.za*
[e] *olakanmie@biust.ac.bw*

Abstract. Knowledge of friction properties of a material is essential in order to understand its tribological applications. The friction is an important aspect that affects functionality of maraging steel components manufactured by laser powder bed fusion (LPBF). Although friction and wear reduces stability and reliability of vulnerable parts, the friction is beneficial in other applications. A response surface methodology (RSM) model was developed in order to predict and optimise the coefficient of friction (COF) of LPBF manufactured maraging steel 300 parts. The model data was obtained from a series of experiments by varying the following LPBF processing variables; laser power, scan speed and hatch spacing. The RSM model results were consistent with the experiment values. A minimum COF value = 0.109 was predicted under LPBF processing parameters laser power = 130 W, scanning speed = 750 mm/s and hatch spacing = 104 μm. Maximum COF = 0.166 was obtained at laser power = 130 W, scanning speed = 400 mm/s and hatch spacing = 110 μm.

***Keywords* -** Maraging Steel 300, Laser Powder Bed Fusion, Coefficient of Friction, Response Surface Methodology, Optimisation.

INTRODUCTION

Maraging steel is generally applied in hot work dies, aircraft components, high speed rocket propelled sleds, rocket motor cases, pressure vessels, bearing and gear housings [1], [2]. Friction and wear significantly influences performance and service life of laser powder bed fusion (LPBF) manufactured maraging steel parts such as bearing gear housings [2].

Friction and wear reduces stability and reliability of susceptible parts such as high speed bearings [3]. However friction is beneficial in applications such as the stamping process. Maximum allowable drawing force can be achieved by the friction between the workpiece and punch [4]. Knowledge of the friction and wear properties of a material is essential in order to understand its tribological applications. He *et al.*, [3] investigated the tribological (friction and wear) properties of 9Cr18Mo bearing steel at different temperature and frictional pair conditions. Severe friction and wear were observed at high temperatures. Bae *et al.*, [2] did a study on the influence of LPBF processing variables on the wear properties of maraging steel bearing gear housings manufactured by LPBF process. Their study focused on the influence of LPBF building direction, counterpart materials and heat treatment conditions. Trzepiecinski, [4] investigated tribological behaviour of strip drawing, draw bead and bending under tension friction tests. The tests were conducted under different dry and lubricated conditions. Orientation of the samples had a significant influence on the coefficient of friction. Sun *et al.*, [1] investigated friction and wear mechanisms of maraging steel 300 under different loads and sliding speeds. Low coefficient of friction was observed at high sliding speed and load. This was attributed

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to the softening of material due to heat generated in the rubbing surfaces. Influence of LPBF processing parameters on the friction and wear behaviour of maraging steel have not been reported in detail.

Many researchers looked into the effect of LPBF process variables and applied heat treatment conditions on the quality properties of built parts. According to Cao, [5] quality properties that were investigated researchers include microstructure, porosity, residual stresses, deformation, surface roughness, tensile strength, elongation and hardness. Quality attributes of parts built by LPBF are influenced by the LPBF processing parameters to a greater extents [6], [7]. Therefore, it is important to find optimal processing parameters to produce parts that meet expected performance requirements. This study focused on three LPBF processing parameters namely laser power, scanning speed and hatch spacing. These parameters were identified as the most influential processing parameters [6], [8], [9].

Many researchers developed models to predict material properties. Response surface methodology (RSM) is an effective tool for modelling correlation of independent variables and responses. The RSM models have successfully provided good prediction abilities. Olakanmi *et al.*, [10] applied RSM to improve characteristic features of laser cladded Inconel 625/WC composite coatings. It was inferred that RSM models can sufficiently predict quality properties of the composite coatings. Ahmed *et al.*, [11] developed a RSM model that predict wear rate to obtain wear test parameters for minimum and maximum wear. Their study investigated dry wear test conditions namely speed, load and sliding distance. The data predicted by RSM was in agreement with experiment results. Developing a model that can predict coefficient of friction (COF) as a function of LPBF processing parameters is necessary to enhance the building of maraging steel parts that can meet functional requirements. The objective of this study was to develop a RSM model which predicts tribological (friction) behaviour of maraging steel 300 parts.

MATERIALS AND METHODS (POWDER)

Maraging steel powder (FE 339 or DIN 1.2709) supplied by Praxair Surface Technologies (Connecticut, USA) was the raw material used for building the samples. TABLE 1 shows typical chemical constitution of the maraging steel (1.2709) powder.

TABLE 1. Chemical make-up of maraging steel (1.2709) powder

Ni	Co	Mo	Ti	Al	Cr	C	Mn, Si	P, S	Fe
17 - 19 wt%	8.5 - 9.5 wt%	4.5 - 5.2 wt%	0.6 - 0.8 wt%	0.05 - 0.15 wt%	≤ 0.5 wt%	≤ 0.03 wt%	≤ 0.1 wt% (each)	≤ 0.01 wt% (each)	balance

EXPERIMENTAL PROCEDURE

A central composite design (CCD) in Minitab 17 was applied in the study to explore the effect of varying the LPBF process variables. The process parameters were varied to low point (-1), zero point (0) and high point (1) (TABLE 2). Low alpha point (-1.6818) and high alpha point (1.6818) were included to investigate the effect of the three factors if one ventures outside the processing parameter range.

TABLE 2. Process parameters explored in this investigation

Factors	**Laser power [W]**	**Scan speed [mm/s]**	**Hatch spacing [µm]**
Designations	A	B	C
High alpha ranking (1.6818)	193.6	852.3	116.8
High ranking (1)	180	750	110
Zero ranking (0)	160	600	100
Low ranking (-1)	140	450	90
Low alpha ranking (-1.6818)	126.4	347.7	83.2
Variation range	20	150	10

20 cuboid samples (with size 10 x 10 x 10 mm) were built varying laser power, scanning speed and hatch spacing as shown in TABLE 3. The 20 experiment runs comprised of 6 central experiment points and 14 axial points. The parts were fabricated on a Concept Laser M2 LaserCUSING machine in a nitrogen gas atmosphere. The machine laser power and scan speed ranges up to 200 W and 5000 mm/s respectively. Laser power, scanning speed and hatch spacing were varied whilst maintaining a constant layer thickness (TABLE 3).

TABLE 3. Central composite design with observed and RSM results

Run	A:Laser Power (W)	B:Scan Speed (mm/s)	C:Hatch Spacing (µm)	A:Laser Power (W)	B:Scan Speed (mm/s)	C:Hatch Spacing (µm)	COF Expt	COF RSM
1	0	0	0	160.0	600.0	100.0	0.137	0.133
2	0	0	1.6818	160.0	600.0	116.8	0.147	0.148
3	0	-0.6818	0	160.0	347.7	100.0	0.145	0.139
4	1.6818	0	0	193.6	600.0	100.0	0.141	0.138
5	0	0	0	160.0	600.0	100.0	0.133	0.133
6	1	-1	1	180.0	450.0	110.0	0.137	0.139
7	0	0	-1.6818	160.0	600.0	83.2	0.148	0.145
8	0	0	0	160.0	600.0	100.0	0.130	0.133
9	1	1	1	180.0	750.0	110.0	0.141	0.143
10	-1	-1	-1	140.0	450.0	90.0	0.143	0.143
11	1	1	-1	180.0	750.0	90.0	0.149	0.151
12	-1	-1	1	140.0	450.0	110.0	0.154	0.154
13	-1	1	1	140.0	750.0	110.0	0.121	0.117
14	-1	1	-1	140.0	750.0	90.0	0.126	0.125
15	0	0	0	160.0	600.0	100.0	0.127	0.133
16	0	1.6818	0	160.0	852.3	100.0	0.127	0.127
17	0	0	0	160.0	600.0	100.0	0.128	0.133
18	-1.6818	0	0	126.4	600.0	100.0	0.121	0.128
19	1	-1	-1	180.0	450.0	90.0	0.122	0.128
20	0	0	0	160.0	600.0	100.0	0.129	0.133

The fabricated parts were polished to P1200 grit paper using mrc MP-1B grinding and polishing machine. Silicon Nitride wear balls of diameter 6.35mm fitted on Rtec Universal tribometer were used for performing the wear test. The tests were conducted under a load of 150 N, 0.1 mm/s² acceleration, 10 minutes dwell time, 1 mm/s velocity and 2 mm sliding distance. The coefficient of friction (TABLE 3) was obtained from the Rtec Universal tribometer analysis application suite.

RSM MODELLING

Montgomery, (2013) defined RSM as a compilation of mathematical and statistical tools which are effective in modelling and examination of situations in which output is determined by numerous process variables. The main objective of RSM is to improve the response. The relationship of the responses and the independent variables (inputs) can be generalised by Equation (1) [12].

$$y = f(x_1, x_2) + \epsilon \tag{1}$$

A second order polynomial regression equation was applied in fitting the experimental data for identifying and describing applicable model terms in this study. The analyses were performed using Minitab 17 software, the model was described by Equation (2) [12].

$$y = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \beta_{ii} {x_i}^2 + \sum_{i<} \sum_{j=2}^{k} \beta_{ij} x_i x_j + \epsilon \tag{2}$$

Where y denotes the predicted response, β_0 is the model intercept coefficient, a_i depict the linear outcome of x_i, a_{ii} signifies the quadratic influence of x_i and a_{ij} stands for the linear-linear relationship of x_i and x_j, k is the number of factors (In this study k = 3), ϵ is residual error.

RESULTS DISCUSSION

Rationality of the model was evaluated by Analysis of Variance (ANOVA) that was performed in Minitab 17 software. Higher F-value and small P value less than 0.05 suggests that the model significantly fits the experimental data. Factors with a large F-value and P value less than 0.05 are also considered relevant. The developed model applied a stepwise regression approach which get rid of insignificant variables automatically. The model F value of 8 and P value of 0.001 suggests that the model is significant (TABLE 4). All the three independent variables (laser power (A), scan speed (B) and hatch spacing (C)) had significant effect on the coefficient of friction. The most significant combined parameters were scan speed * scan speed (B^2), laser power * scan speed, (AB) and scan speed * hatch spacing (BC).

TABLE 4. ANOVA of the model

Source	Sum of squares	df	Mean squares	F-value	P-value prob>F
Model	0.001658	6	0.000276	8.00	0.001 significant
Linear	0.000294	3	0.000098	2.84	0.079
A	0.000116	1	0.000116	3.86	0.090
B	0.000169	1	0.000169	4.90	0.045
C	0.000009	1	0.000009	0.25	0.623
Square	0.000336	1	0.000336	9.72	0.008
B^2	0.000336	1	0.000336	9.72	0.008
2-way interaction	0.001029	2	0.000515	14.90	0.000
AB	0.000834	1	0.000834	24.15	0.000
BC	0.000195	1	0.000195	5.65	0.033
Residual error	0.000449	13	0.000035		
Lack of Fit	0.000189	8	0.000024	0.46	0.845 not significant
Pure Error	0.000260	5	0.000052		
Cor Total	0.002107	19			
Std. Dev.	0.0058765				
R^2		0.7870			
Adjusted R^2		0.6886			
Predicted R^2		0.5712			

Adequacy and fitness of the model was signified by coefficient of determination R^2 value of 0.7870, adjusted R^2 value of 0.6886 and predicted R^2 value of 0.5712 (TABLE 4). R^2 value of 0.7870 indicates a robust correlation of the experiment results and predicted values of coefficient of friction (FIGURE 1). The difference between the adjusted R^2 value of 0.6886 and predicted R^2 value of 0.5712 is < 0.2 indicating that they are in reasonable agreement. The regression Equation (3) indicates the empirical relationship of the coefficient of friction and the LPBF processing parameters after eliminating non-significant factors with the standard deviation of ± 0.00588.

$$\textit{Coefficient of friction} = 0.13267 + 0.00291\,A - 0.00352\,B + 0.00080\,C + 0.00478\,C^2 + 0.01021\,AB - 0.00494\,BC \quad (3)$$

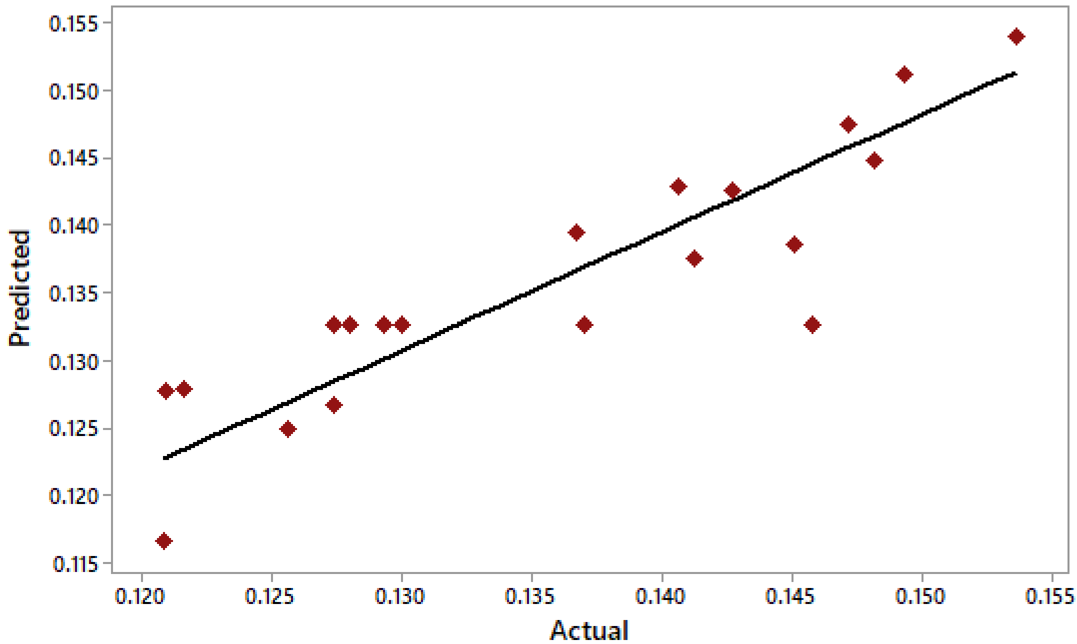

FIGURE 1. Predicted vs. observed values of COF

COMPARISON OF RSM MODEL PREDICTIONS WITH EXPERIMENTAL VALUES

The comparison of the RSM predicted and experimental values was presented in FIGURE 2. The model has a good predicting ability, the RSM predicted and experimental values are in good agreement.

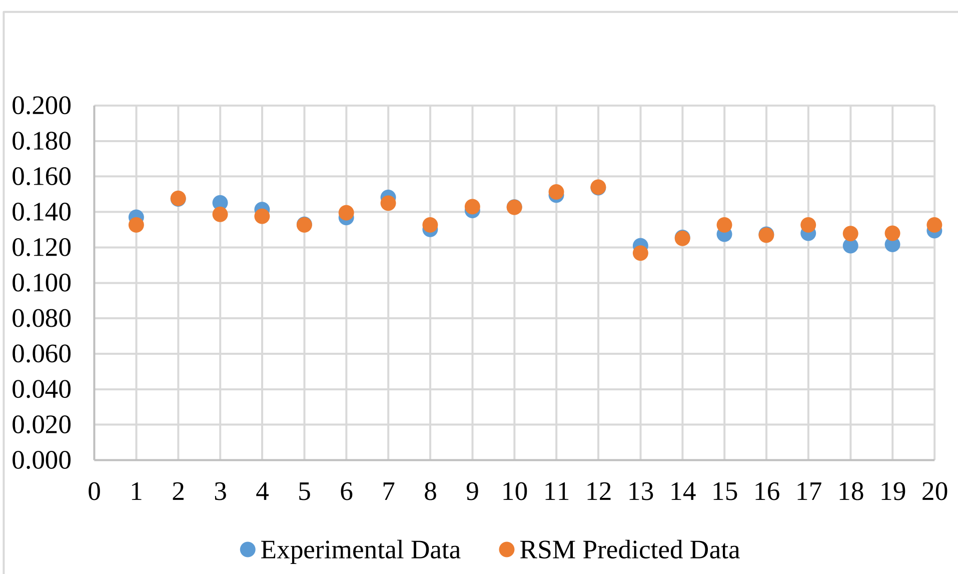

FIGURE 2. Comparison of predicted values with experimental data

TESTING OF RSM MODEL

Independent test data set of RSM model (sample number 2, 5, 10, 14 and 20) were arbitrarily chosen from the experiment data in TABLE 3. Applicability of the model was further tested by comparing the RSM test results with experiment results (FIGURE 3).

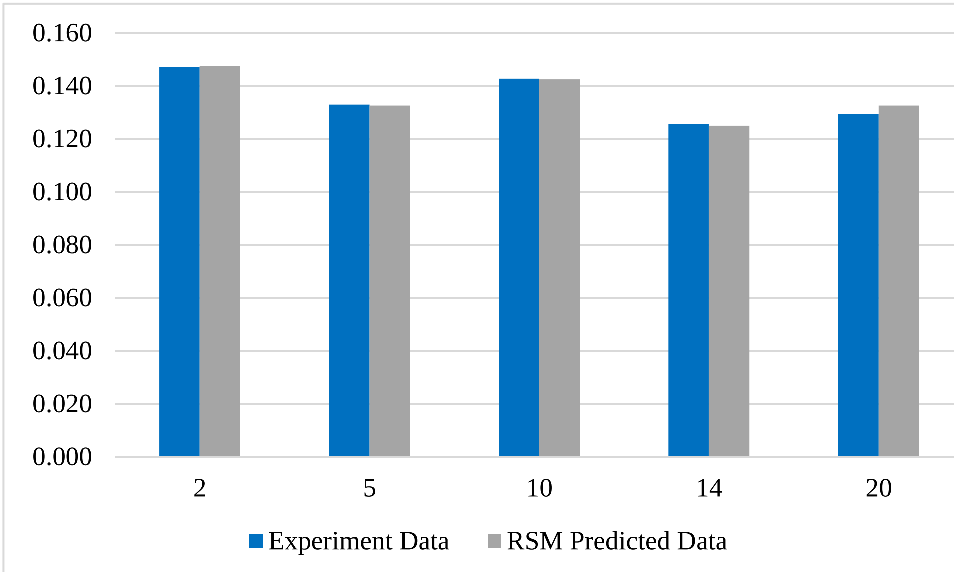

FIGURE 3. Comparison of RSM test results with experimental values

The estimated test results are good and in consensus with the experiment results. The percentage relative error varied from -0.52 to +2.59 TABLE 5.

TABLE 5. Relative error of test results vs experiment data

Sample	**2**	**5**	**10**	**14**	**20**
Experiment Data	0.147	0.133	0.143	0.126	0.129
RSM Predicted Data	0.148	0.133	0.143	0.125	0.133
Relative Error (%)	0.22	-0.23	-0.14	-0.52	2.59

OPTIMISATION

The RSM model was used to obtain LPBF optimal processing parameters to minimise and maximise coefficient of friction and can be observed in TABLE 6 and TABLE 7 respectively. The selected optimum processing parameter for minimum COF was solution 1 (TABLE 6). COF value = 0.109 was predicted under operating conditions laser power = 130 W, scanning speed = 750 mm/s and hatch spacing = 104 µm.

TABLE 6. Optimum parameters for minimum COF

Solution	Power (W)	Scan speed (mm/s)	Hatch spacing (µm)	COF	Desirability	Selected
1	**130**	**750**	**104**	**0.109**	**1.00**	**X**
2	130	750	90	0.118	1.00	
3	134	750	90	0.121	1.00	
4	180	400	92	0.124	0.91	
5	180	400	91	0.124	0.91	
6	152	722	104	0.125	0.88	
7	164	643	98	0.133	0.63	
8	151	600	92	0.134	0.61	
9	133	456	97	0.144	0.30	

Solution 1 (TABLE 7) was the selected optimum processing parameters for maximum COF = 0.166 with desirability value of 1. The LPBF independent variables are laser power = 130 W, scanning speed = 400 mm/s and hatch spacing = 110 µm.

TABLE 7. Optimum parameters for maximum COF

Solution	Power (W)	Scan speed (mm/s)	Hatch spacing (µm)	COF	Desirability	Selected
1	**130**	**400**	**110**	**0.166**	**1.00**	**X**
2	152	400	110	0.154	1.00	
3	135	466	110	0.154	1.00	
4	180	750	90	0.151	0.93	
5	130	400	90	0.151	0.91	
6	133	400	90	0.149	0.87	
7	180	750	110	0.143	0.67	
8	172	410	110	0.143	0.67	
9	155	603	90	0.136	0.46	

CONCLUSIONS

An attempt has been made to apply RSM in order to predict and optimise the COF of LPBF manufactured maraging steel 300 parts. CCD in Minitab 17 was applied to conduct the friction tests. The data obtained from the tests was used to build up a RSM model. Adequacy and fitness of the model was verified by ANOVA and regression analysis. The model F value of 8, P value of 0.001 and coefficient of determination R^2 value of 0.7870 indicated reliability of the model. The accuracy of the RSM model was further verified by comparing the model predicted results with experiment data. The model was tested with independent data set, the projected values are consistent with the values obtained from experiments. The most desirable optimum LPBF processing parameters for minimum COF value = 0.109 was predicted under operating conditions laser power = 130 W, scanning speed = 750 mm/s and hatch spacing = 104 µm.

Maximum COF = 0.166 was obtained at laser power = 130 W, scanning speed = 400 mm/s and hatch spacing = 110 μm. These parameters applies to the specific material and machine.

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